

Optimization, design and control of a photovoltaic/wind turbine/battery system in Mediterranean climate conditions

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ABSTRACT

The goal of this study is to design and optimize a photovoltaic/wind turbine/batteries system. The application is made in the area of Bejaia (Algeria), a Mediterranean region where the solar and wind energy are extremely exploitable in this area due to its geographical location. The total incident energy approach was used to develop the device under consideration. To optimize power, the fuzzy logic control (FLC) is applied and to highlight the benefits of this maximum power point tracking (MPPT) strategy, it was compared to perturb and observe (P&O) method. A power management control has been applied. The findings from the three different days are displayed and analyzed to demonstrate the applicability of the suggested system. The examined system is assessed using the Homer software to demonstrate the best feasible integration of the several sources at the Bejaia location. There has been an increase in renewable power, which is one of the study's key novelty and objectives, so less stress on batteries in a PV/wind system. This is owing to the suggested accurate sizing procedure and to the FLC algorithm. The findings of the suggested study under various solar irradiation and wind speed velocity profiles are presented to demonstrate its applicability.

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1. INTRODUCTION

Electrical production by wind and photovoltaic is intermittent, which makes the power system more complicated. So, storage is important to feed power demand and by storing excess energy and generating energy when it is needed. It is obtained hybrid system more reliable and environmentally friendly [1]. To avoid these problems, a maximizing power approach is used. It is obtained a maximum load power despite variations in solar irradiation and wind speeds [2]-[7]. A great diversity of optimization methods has been adopted to track the photovoltaic panels and wind turbines powers [8]-[10]. The proposed strategy optimization is the fuzzy logic control (FLC) method and it is compared to perturb and observ (P&O) method. Power management strategies (PMS) are often used to control the load and the various power sources. Various methods have been proposed [11]-[30]. Some of them are synthesis of the most significant supervisory controls [11]-[20] and others in the two latest years are focused on a very precise method and defined systems [21]-[30].

In this paper, study on optimization, design, control and of a hybrid solar system with wind turbine and batteries is given. To determine the best design for the studied hybrid system, Homer pro software is applied. The suggested optimization strategy is based on FLC. The study's key features and goals can be summarized as a considerable increase in renewable power, so less stress on batteries in PV/wind system. This is due to the suggested accurate sizing approach and to the FLC algorithm. The studied system is described in section 2. Parameters identification is given in section 3. Measurements of weather conditions are given in section 4. Results of optimization methods and the power management control are discussed in section 5. Economic study using Homer pro software is presented in section 6 and at last the conclusion in section 7.

2. STUDIED SYSTEM DESCRIPTION

It is composed by a photovoltaic generator, a wind turbine, converters (DC/DC, DC/AC), batteries storage and a load Figure 1. To optimize power, the FLC is applied and to highlight the benefits of this maximum power point tracking (MPPT) strategy.

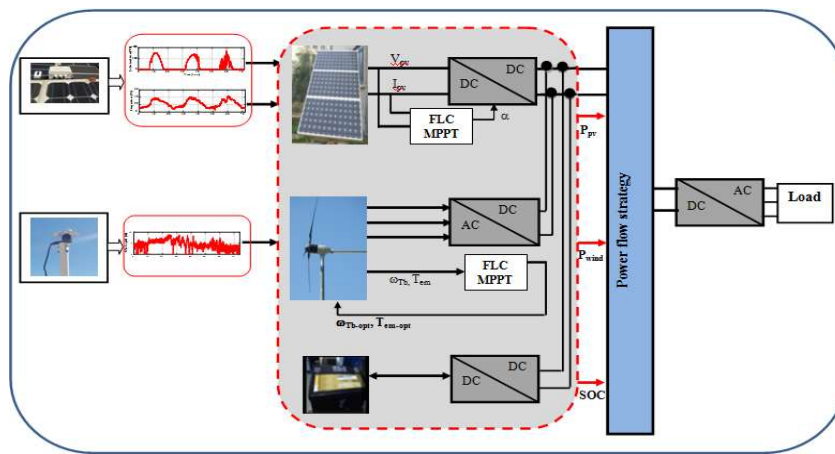


Figure 1. Studied system

3. PARAMETERS IDENTIFICATION

3.1. Wind turbine

A wind turbine and a permanent magnetic synchronous generator (PMSG) with a diode bridge rectifier compose the wind system. In the laboratory, it is proceeded the following tests Figure 2. The mechanical power can be written as [4].

$$P_{Tb} = \frac{1}{2} \cdot C_p(\lambda) \cdot \rho \cdot S \cdot V_{wind}^3 \quad (1)$$

where ρ is air density (kg/m^3), S is section area (m^2), V_{wind} is wind speed velocity (m/s).

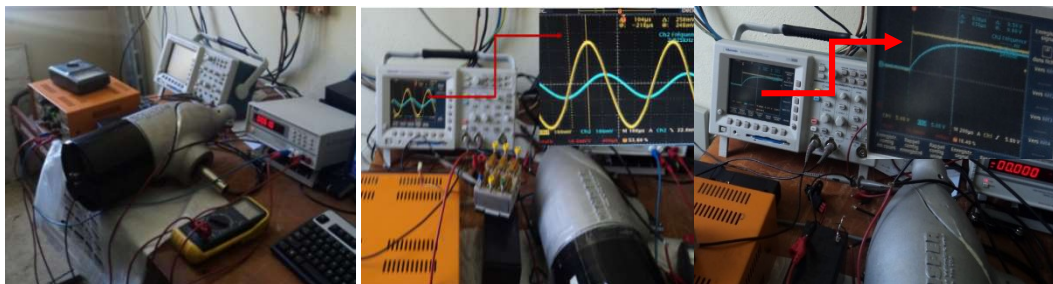


Figure 2. Wind turbine tests at the laboratory

The mechanical in (2) is [30]:

$$J \frac{d\omega_m}{dt} = T_m - T_e - f\omega_m \quad (2)$$

T_e electromagnetic torque (N.m), J total inertia (kg/m²), T_m turbine's mechanical torque (N.m) and f viscous friction coefficient (N.m.s rad⁻¹). The electromagnetic torque generator T_e is [30]:

$$T_e = \left(\frac{3}{2}\right)P(L_d - L_q)I_{sd} \cdot I_{sq} + \Phi_f I_{sq} \quad (3)$$

3.2. Photovoltaic system

The used panels are 175 Wp and the current of single diode model is given by [2]:

$$I_{pv} = I_{ph} - I_0 \times \left[\exp \left(\frac{q \times (V_{pv} + R_s \times I_{pv})}{A \times N_s \times K \times T_j} \right) - 1 \right] - \frac{V_{pv} + R_s \times I_{pv}}{R_{sh}} \quad (4)$$

where I_{ph} is the photo-current (A), I_d the diode-current (A) and I_{Rsh} the shunt current (A). The following test bench Figure 3 is used to establish electrical parameters for PV panels.

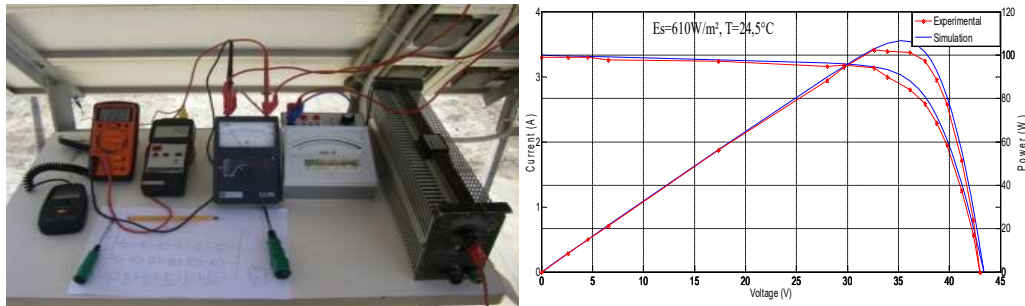


Figure 3. PV Experimental bench and electrical characteristics at $E_s=610 \text{ W/m}^2$, $T=24.5 \text{ }^\circ\text{C}$

3.3. Battery system

As seen in Figure 4, this model is defined by a succession of electromotive forces that are set with a variable resistor. The battery voltage is represented as [6]:

$$V_{batt} = E_b - R_b \cdot I_{batt} - K \int \left(\frac{I_{batt}}{Q} \right) dt \quad (5)$$

$$SOC = 1 - \frac{I_{batt} \cdot t}{C_{batt}} \quad (6)$$

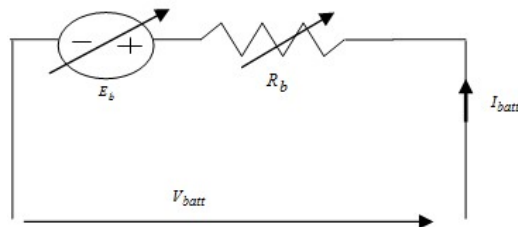


Figure 4. Lead acid battery model

4. MEASUREMENTS OF WEATHER CONDITIONS

Measurements of weather conditions were made for three different days Figures 5. The simulations are run in MATLAB using the measured solar irradiance in Figure 6(a), wind speeds profile in Figure 6(b) and ambient temperature in Figure 6(c).

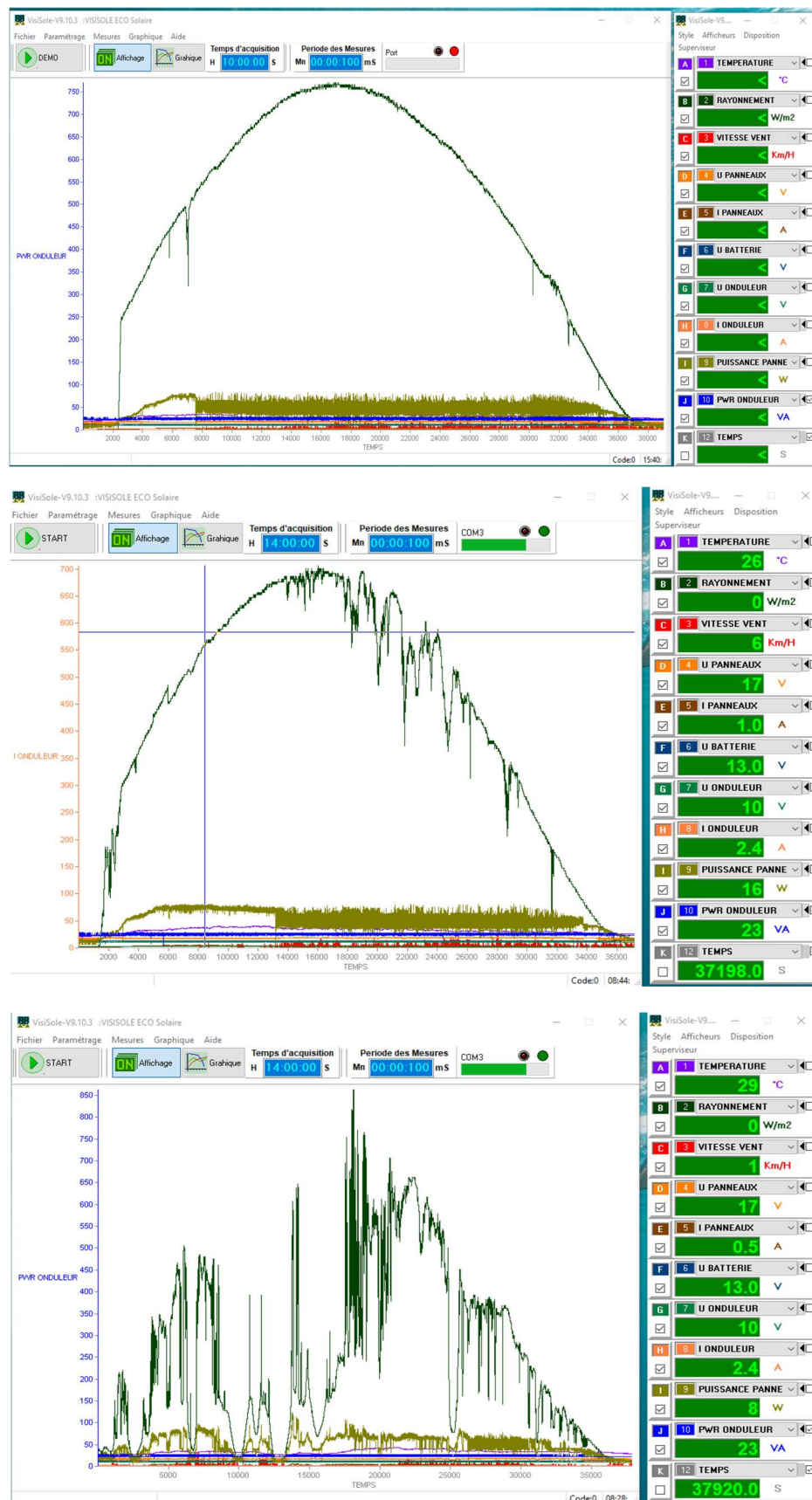


Figure 5. Measured solar irradiance and wind speeds profile during

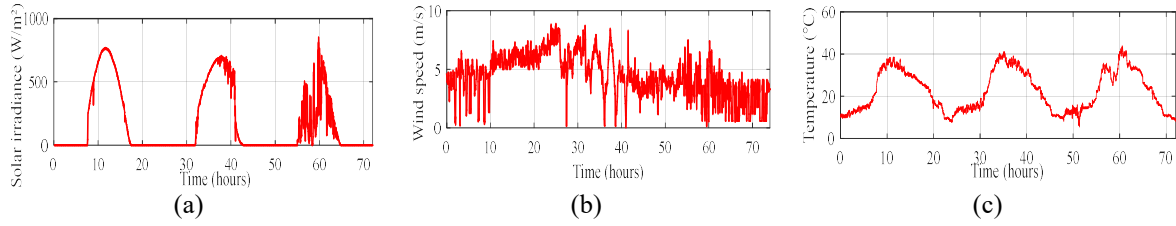


Figure 6. Simulation measurements

5. RESULTS AND DISCUSSION

5.1. Optimization strategies

5.1.1. P&O strategy

P&O strategy is one of the most common used approaches [1]. Although very simple to use and requiring no prior knowledge of photovoltaic parameters, this increase oscillations at steady state. The algorithm is:

$$\Delta P_{pv} > 0 \text{ and } \Delta V_{pv} > 0 \text{ thus } \Delta P_{pv} / \Delta V_{pv} > 0, D = D + \Delta D$$

$$\Delta P_{pv} < 0 \text{ and } \Delta V_{pv} < 0 \text{ thus } \Delta P_{pv} / \Delta V_{pv} < 0, D = D - \Delta D$$

$$\Delta P_{pv} = 0 \text{ and } \Delta V_{pv} = 0 \text{ thus } \Delta P_{pv} / \Delta V_{pv} = 0, \Delta D = 0, D = D$$

5.1.2. FLC method

The two inputs to the controller system are the error and the change in error. For PV generators, it's flowchart is shown in Figure 7(a), and for wind generators, it's displayed in Figure 7(b). In PV generator:

$$\begin{cases} E(k) = \frac{P_{pv}(k+1) - P_{pv}(k)}{V_{pv}(k+1) - V_{pv}(k)} \\ CE(k) = E(k+1) - E(k) \end{cases} \quad (7)$$

In wind turbines, the regulations are based on changes in wind speed and power:

$$\begin{cases} \Delta \omega_{Tb} = \omega_{Tb}(k) - \omega_{Tb}(k-1) \\ \Delta P_{Tb} = P_{Tb}(k) - P_{Tb}(k-1) \\ \omega_{Tb-ref} = \omega_{Tb}(k-1) + \Delta \omega_{Tb}(k) \end{cases} \quad (8)$$

the output turbine power and its rotational speed are indicated by $P_{Tb}(k)$ and $\omega_{Tb}(k)$, respectively, and the instant of reference speed is designated by $\Delta \omega_{Tb,ref}(k)$.

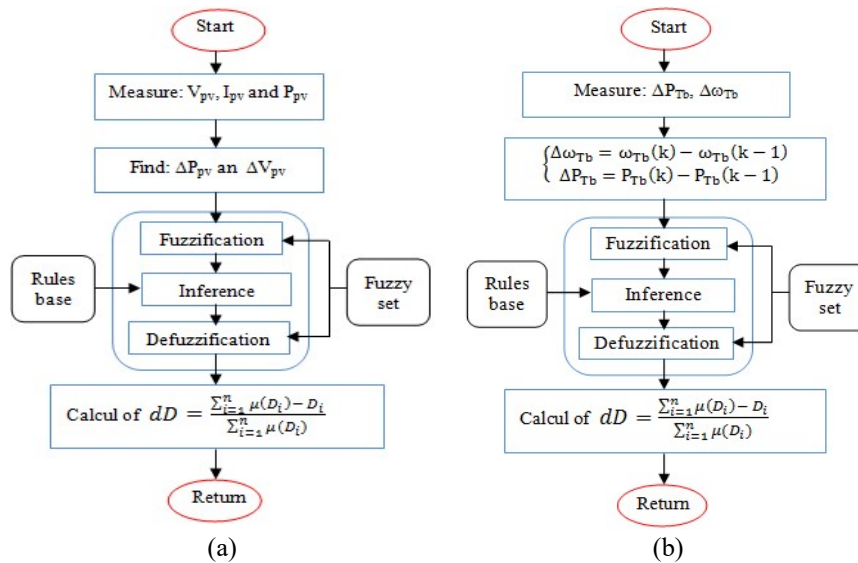


Figure 7. FLC flowchart (a) PV generator and (b) wind generator

It is observed in Figure 8(a) significant power gains in hybrid power up to 161 W due to the savings in wind Figure 8(b) and photovoltaic powers Figure 8(c) when FLC is used. Figures 9(a) to (c) and Figures 10(a) to (c) provide a comparison of the two methods' effectiveness, power consumption and response times. The FLC generates maximum power, less response time and best efficiency.

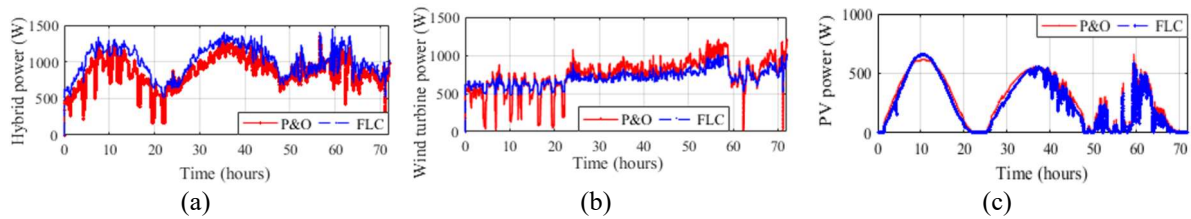


Figure 8. Obtained powers

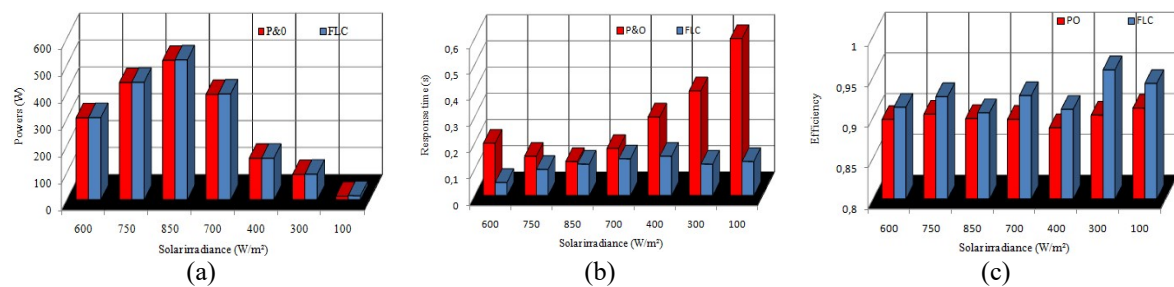


Figure 9. Comparison performances for PV system

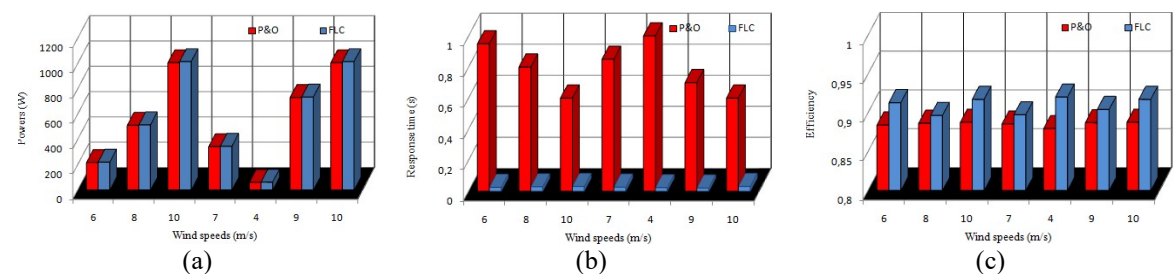


Figure 10. Comparison performances for wind turbine system

5.2. Power management control

The supervisory power approach is used to control the various powers. Our study is mainly based on previous works [11]-[14]. It is observed that the various sources have been effectively handled and that the batteries have experienced reduced stress Figure 11.

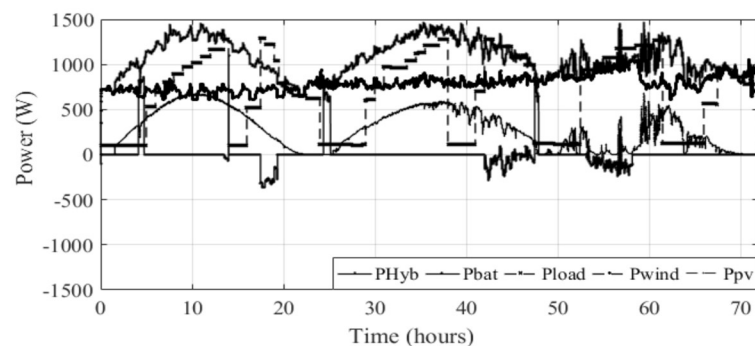


Figure 11. Different powers supplying the load using FLC strategy

Optimization Results											
Left Double Click on a particular system to see its detailed Simulation Results.											
Architecture								Cost			
PV (kW)	G1	1kWh LA	Converter (kW)	Efficiency1	Dispatch	NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)	O&M (\$/yr)	
0.960		2	1.00	1.00	CC	\$2,525	\$0.828	\$21.53	\$2,247	\$0.773	
0.960	1	2	1.00	1.00	CC	\$6,096	\$2.00	\$75.26	\$5,123	\$3.09	

Figure 15. Proposed optimized architecture

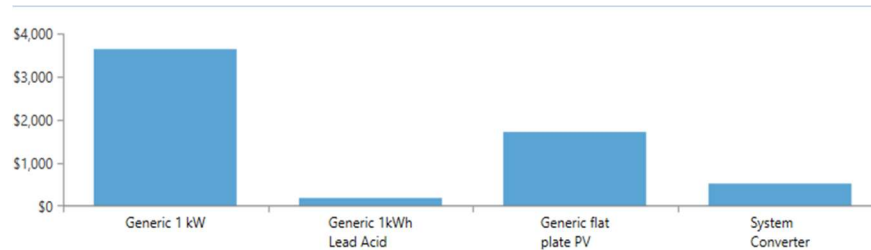


Figure 16. Categorized optimized result by HOMER

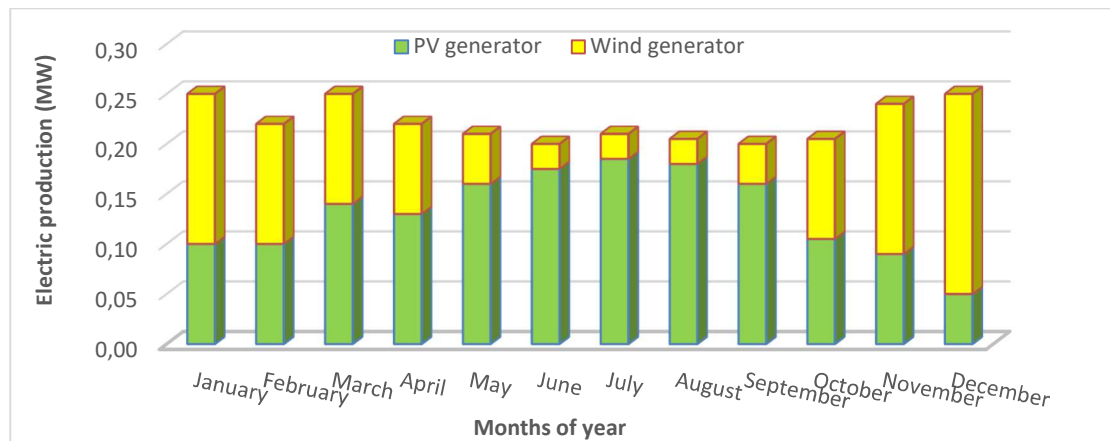


Figure 17. Monthly electric production from the system

Table 2. The fraction of photovoltaic/wind energy

Subsystem	Production (kWh/year)	Fraction (%)
PV array	1643	62.1
Wind turbine	1002	37.9
Total	2644	100

The consumption is 2360 kWh/year by the supplied AC load. The batteries store the extra energy generated by the two sources, as illustrated in Table 3. The photovoltaic and wind energy production can be represented in Figure 18. It is observed a low production from 0.26 kW to 0.46 kW, then it increases until it reaches 0.85 kW.

Table 3. Load energy consumption and excess electricity

Consumption	kWh/year	%
AC load	2360	100
Excess energy	284	12.03

The energy production is considerable by the wind turbine during winter and autumn seasons. It reaches the maximum value in January around 1 kW. The battery is an important component of this electrical system, it is used throughout the day, with its charge state ranging from 30% to 90% Figure 19.

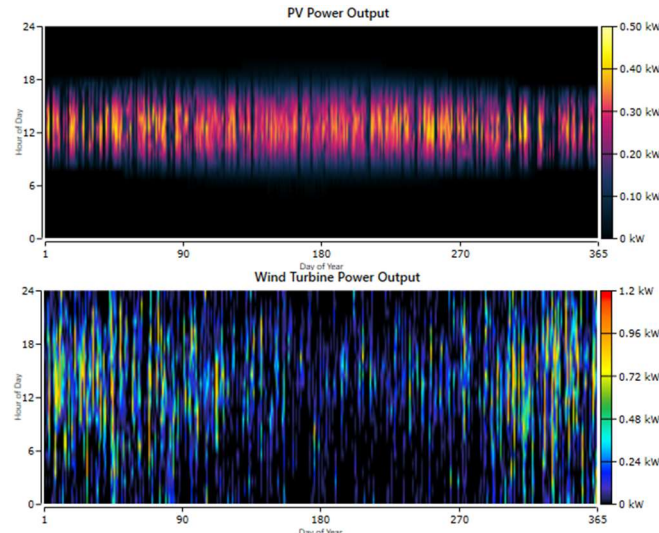


Figure 18. Distribution of photovoltaic and wind energy during a year

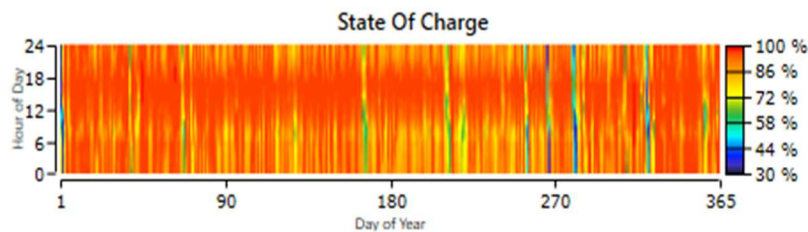


Figure 19. Battery state of charge during a year

7. CONCLUSION

The design, optimization, control, and feasibility of a solar system with a wind turbine with batteries are discussed in this study. An application has been made on three distinct days in the Bejaia area. Homer Po has presented the best solution based on calculations. Different findings have been compared and analyzed. It is noticed that the batteries have not been required too much due to correct sizing and gain saving in power by using FLC strategy and the power supervision method. Indeed, the gain in power allowed to change the priority of the tests of the proposed algorithm by using the batteries as much as possible and by charging them when it is possible with the power excess. It can be concluded that the different sources were managed in an optimal way in order to meet the load demand regardless weather variations. The findings are very promising and can be used to enhance PV/wind/battery installations' technological and economic efficiency in Bejaia area and around the Mediterranean region. In the future, it will be interesting to develop an application for water pumping in agriculture.




REFERENCES

- [1] A. Z. AL Shaqsi, K. Sopian, A. Al-Hinai, "Review of energy storage services, applications, limitations, and benefits," *Energy Reports*, vol. 6, pp. 288–306, Dec. 2020, doi: 10.1016/j.egy.2020.07.028.
- [2] D. Rekioua, T. Rekioua, and Y. Soufi, "Control of a grid connected photovoltaic system," *2015 International Conference on Renewable Energy Research and Applications (ICRERA)*, 2015, pp. 1382–1387, doi: 10.1109/ICRERA.2015.7418634.
- [3] J. Riahi, S. Vergura, D. Mezghani, and A. Mami, "Smart and renewable energy system to power a temperature-controlled greenhouse," *Energies*, vol. 14, no. 17, pp. 5499–5520, Sep. 2021, doi:10.3390/en14175499.
- [4] K. Idjdarene, D. Rekioua, T. Rekioua, and A. Tounzi, "Wind energy conversion system associated to a flywheel energy storage system," *Analog Integrated Circuits and Signal Processing*, vol. 69, no. 1, pp.67–73, Mar. 2011, doi: 10.1007/s10470-011-9629-2.
- [5] W. Qi, J. Liu, X. Chen, and P. D. Christofides, "Supervisory predictive control of standalone wind/solar energy generation systems," in *IEEE Transactions on Control Systems Technology*, vol. 19, no. 1, pp. 199–207, Jan. 2011, doi: 10.1109/TCST.2010.2041930.
- [6] V. Salas, E. Olias, A. Barrado and A. Lazaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems," *Solar energy materials and solar cells*, vol. 90, no. 11, pp. 1555-1578, July 2006. doi: 10.1016/j.solmat.2005.10.023




- [7] K. Uhlen, B. A. Foss, and O. B. Gjosaeter, "Robust control and analysis of a wind-diesel hybrid power plant," in *IEEE Transactions on Energy Conversion*, vol. 9, no. 4, pp. 701-708, Dec. 1994, doi: 10.1109/60.368338.
- [8] D. Kumar and K. Chatterjee, "A review of conventional and advanced MPPT algorithms for wind energy systems," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 957-970, Mar. 2016, doi: 10.1016/j.rser.2015.11.013.
- [9] A. G. Abo-Khalil and A.S. Alghamdi, "MPPT of permanent magnet synchronous generator in tidal energy systems using support vector regression," *Sustainability*, vol. 13, no. 4, pp. 1-15, Feb. 2021, doi: 10.3390/su13042223.
- [10] M. S. Wasim, M. Amjad, S. Habib, M. A. Abbasi, A. R. Bhatti, and S. M. Mueyee, "A critical review and performance comparisons of swarm-based optimization algorithms in maximum power point tracking of photovoltaic systems under partial shading conditions," *Energy Reports*, vol. 8, Nov. 2022, pp. 4871-4898, doi: 10.1016/j.egyr.2022.03.175.
- [11] A. Kaysal, S. Koroglu, and Y. Oguz, "Hierarchical energy management system with multiple operation modes for hybrid DC microgrid," *International Journal of Electrical Power and Energy Systems*, vol. 141, Oct. 2022, doi: 10.1016/j.ijepes.2022.108149.
- [12] E. Kamal and L. Adouane, "Intelligent Energy Management Strategy Based on Artificial Neural Fuzzy for Hybrid Vehicle," in *IEEE Transactions on Intelligent Vehicles*, vol. 3, no. 1, pp. 112-125, March 2018, doi: 10.1109/TIV.2017.2788185.
- [13] A. Achour, D. Rekioua, A. Mohammedi, Z. Mokrani, T. Rekioua, and S. Bacha, "Application of direct torque control to a photovoltaic pumping system with sliding-mode control optimization," *Electric Power Components and Systems*, vol. 44, no. 2, pp. 172-184, Jan. 2016, doi: 10.1080/15325008.2015.1102182.
- [14] N. Mebarki, T. Rekioua, Z. Mokrani, D. Rekioua, and S. Bacha, "PEM fuel cell/battery storage system supplying electric vehicle," *International Journal of Hydrogen Energy*, vol. 41, no. 45, pp. 20993-21005, Dec. 2016, doi: 10.1016/j.ijhydene.2016.05.208.
- [15] K. Krishnamurthy, S. Padmanaban, F. Blaabjerg, R. B. Neelakandan, and K. R. Prabhu, "Power Electronic Converter Configurations Integration with Hybrid Energy Sources—A Comprehensive Review for State-of-the-Art in Research," *Electric Power Components and Systems*, vol. 47, no. 18, Nov. 2019, pp. 1623-1650, doi: 10.1080/15325008.2019.1689457.
- [16] M. S. Ismail, M. Moghavvemi, T. M. I. Mahlia, K. M. Muttaqi, and S. Moghavvemi, "Effective utilization of excess energy in standalone hybrid renewable energy systems for improving comfort ability and reducing cost of energy: a review and analysis," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 726-734, Feb. 2015, doi: 10.1016/j.rser.2014.10.051.
- [17] M. Farhadi and O. Mohammed, "Adaptive Energy Management in Redundant Hybrid DC Microgrid for Pulse Load Mitigation," in *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 54-62, Jan. 2015, doi: 10.1109/TSG.2014.2347253.
- [18] S. Abedi, A. Alimardani, G. Gharehpetian, G. Riahy, and S. Hosseini, "A comprehensive method for optimal power management and design of hybrid RES-based autonomous energy systems," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3, pp. 1577-1587, Apr. 2012, doi: 10.1016/j.rser.2011.11.030.
- [19] B. Robyns, A. Davigny, and C. Saudemont, "Methodologies for supervision of hybrid energy sources based on storage systems—a survey," *Mathematics and Computers in Simulation*, vol. 91, pp. 52-71, May 2013, doi: 10.1016/j.matcom.2012.06.014.
- [20] D. Mazzeo, N. Matera, P. De Luca, C. Baglivo, P.M. Congedo, and G. Oliveti, "A literature review and statistical analysis of photovoltaic-wind hybrid renewable system research by considering the most relevant 550 articles: An upgradable matrix literature database," *Journal of Cleaner Production*, vol. 295, p. 126070, May 2021, doi: 10.1016/j.jclepro.2021.126070.
- [21] K. M. Kotb, M. F. Elmorshedy, H. S. Salama, and A. Dan, "Enriching the stability of solar/wind DC microgrids using battery and superconducting magnetic energy storage based fuzzy logic control," *Journal of Energy Storage*, vol. 45, Jan. 2022, doi: 10.1016/j.est.2021.103751.
- [22] A. N. Abdalla et al., "Integration of energy storage system and renewable energy sources based on artificial intelligence: An overview," *Journal of Energy Storage*, vol. 40, p. 102811, Aug. 2021, doi: 10.1016/j.est.2021.102811.
- [23] A. Elmoutamid, R. Ouladsine, M. Bakhouya, N. El Kamoun, M. Khaidar, and K. Zine-Dine, "Review of control and energy management approaches in micro-grid systems," *Energies*, vol. 14, no. 1, p. 168, Jan. 2021, doi: 10.3390/en14010168.
- [24] N. Bahri and W. O. Amor, "Intelligent power supply management of an autonomous hybrid energy generator," *International Journal of Sustainable Engineering*, vol. 12, no. 5, pp. 312-332, Mar. 2019, doi: 10.1080/19397038.2019.1581852.
- [25] M. F. Elmorshedy, M. R. Elkadeem, K. M. Kotb, I. B. M. Taha, and D. Mazzeo, "Optimal design and energy management of an isolated fully renewable energy system integrating batteries and supercapacitors," *Energy Conversion and Management*, vol. 245, p. 114584, Oct. 2021, doi: 10.1016/j.enconman.2021.114584.
- [26] M. A. Alotaibi and A. M. Eltamaly, "A smart strategy for sizing of hybrid renewable energy system to supply remote loads in Saudi Arabia," *Energies*, vol. 14, no. 21, p. 7069, Oct. 2021, doi: 10.3390/en14217069.
- [27] L. S. Azuara-Grande, S. Arnaltes, J. Alonso-Martinez, and J. L. Rodriguez-Amenedo, "Comparison of two energy management system strategies for real-time operation of isolated hybrid microgrids," *Energies*, vol. 14, no. 20, p. 6770, Oct. 2021, doi: 10.3390/en14206770.
- [28] A. Kumar, R. K. Khadanga, and S. Panda, "Reinforced modified equilibrium optimization technique-based MS-PID frequency regulator for a hybrid power system with renewable energy sources," *Soft Computing*, vol. 26, no. 11, pp. 5437-5455, Jun. 2022, doi: 10.1007/s00500-021-06558-8.
- [29] O. Erdinc et al., "Experimental performance assessment of a non line energy management strategy for varying renewable power production suppression," *International Journal of Hydrogen Energy*, vol. 37, no. 6, pp. 4737-4748, Mar. 2012, doi: 10.1016/j.ijhydene.2011.12.042.
- [30] D. Rekioua and T. Rekioua, "DSP-controlled direct torque control of induction machines based on modulated hysteresis control," *2009 International Conference on Microelectronics-ICM*, 2009, pp. 378-381, doi: 10.1109/ICM.2009.5418603.
- [31] HOMER Energy is now UL, "Optimize the value of your hybrid power system—from utility-scale and distributed generation to standalone microgrids," [Online]. Available: <http://www.homerenergy.com>.

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